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LAVIC LAKE, BULLION AND RELATED FAULTS

San Bernardino County, California

by
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INTRODUCTION

On October 16, 1999 a M7.1 earthquake occurred in the Mojave Desert region of southern California (Figure 1). The earthquake occurred within the eastern California shear zone (ECSZ) which is, in this region, a zone of NNW oriented shear (Sauber and others, 1986; Dokka and Travis, 1990) underlying a pre-existing NW-trending pattern of faults. The 1992 Landers earthquake occurred on other faults within this shear zone, to the west. The faults involved in the 1999 earthquake area were previously evaluated by Hart (1987a,c) and Bortugno (1987). Some of the faults to the west were re-evaluated following the Landers earthquake (Bryant, 1992 & 1994; Hart, 1994).

The Hector Mine earthquake had its epicenter within the U.S. Marine Corps Air Ground Combat Center, Twentynine Palms (MCAGCC). 48 km of co-seismic ground rupture occurred along the Bullion fault and a previously mapped (Dibblee, 1966, 1967b, 1967c), but unnamed, fault which splays northward from the Bullion fault. Ground rupture also occurred on two faults southwest of the Bullion fault. Surface faulting occurred within the Deadman Lake NW, Deadman Lake SW, Hector, Hidalgo Mountain, Lavic Lake, Lavic SE, and Sunshine Peak 7.5-minute quadrangles (Figures 2a and 2b). Additional ground fracturing was observed and evaluated within the Deadman Lake SE, Hector, Lavic Lake and Sleeping Beauty quadrangles.

The purpose of this report is to document the primary surface fault rupture which resulted from the 16 October 1999 Hector Mine earthquake and to present this information as it relates to zoning under the authority of the Alquist-Priolo Earthquake Fault Zone Act (Hart and Bryant, 1997). Emphasis is on the zone of principal fault rupture and reported or observed zones of fracturing that are not within current Earthquake Fault Zones (EFZ). Some additional faults within the earthquake area are also evaluated. This report may be considered supplementary to FER-188 (Hart, 1987a).

SUMMARY OF AVAILABLE DATA (pre-1999)

Earlier work in the area was summarized thoroughly by Hart (1987a). Geologic mapping of the area affected by ground rupture was published by the U.S. Geological Survey (Dibblee, 1966, 1967b, 1967c, Dibblee & Bassett, 1966). These maps depict the Bullion fault as well as much of what is now being named the Lavic Lake fault within the Bullion Mountains and to the south as the latter fault merges with the Bullion fault (Figures 2a,b). To the south, the Bullion fault divides into two, discontinuously expressed, sub-parallel strands which Bacheller (1978) called the West and East Bullion faults (Figure 2b). Dibblee (1967b) also mapped three faults south and west of

Deadman Lake (Figure 2b), the westernmost of which is the Hidalgo fault (also called the Surprise Spring fault by Moyle, 1984) and the easternmost of which now appears to be the northern extension of the Mesquite Lake fault zone. The middle fault was later referred to as fault “A” by Bortugno (1987). These three faults are shown to displace Pleistocene and older deposits yet are concealed by younger alluvium (Dibblee, 1967b).

The northern extent of the Lavic Lake fault, across the Lavic Lake basin, was not previously recognized, although a possible northern continuation of the fault (Figure 2a, fault “B”) was mapped north of the Pisgah crater lava flows (Dibblee and Bassett, 1966). Wise (1969) mapped another fault to the southeast, within the lava flows north of Lavic Lake (Figure 2a). An unnamed fault on the Morgans Well quadrangle (Figures 2a,b) that is roughly on trend (to the southeast) with the NW-oriented portion of the Lavic Lake fault was also previously mapped by Dibblee (1967a).

Reconnaissance mapping (based on aerial photo interpretation) by Morton and others (1980), identified young-looking fault features along the Bullion fault as well as the southernmost part of the Lavic Lake fault (as it joins the Bullion fault). Their work also identified scarps and possible scarps along two of Dibblee’s (1967b) faults south and west of Deadman Lake (northern projection of the Mesquite Lake fault and fault “A” of Bortugno – Figure 2b).

The only detailed site studies, prior to the earthquake, were on the Mesquite Lake fault, south of the main study area. A fault study by Rasmussen and Assoc. (1983) located faulting associated with the Mesquite Lake fault (Plate 9, locality 9b). They found a broad zone of faults (more than 100 m wide) within their trenches (only one trench shown here), with offset of Pleistocene alluvium but no observed offset of overlying Holocene deposits. However, as is evident from the location of their trenches (centered around the main trench shown on Plate 9), they apparently did not intersect the main fault traces. Hart (1987b) noted that “[t]he northwestern extension of the Mesquite Lake fault in the Deadman Lake SE quadrangle is largely a wide zone of faults associated with the Deadman Lake depression” (Plate 9).

Evaluation of the faults in this region by Bortugno (1987) and Hart (1987a,c) led to zoning of several of the faults, including the Bullion fault, Pisgah fault, two of the faults west of Deadman Lake (fault “A” and the Hidalgo fault) and a fault north of Pisgah Crater mapped by Dibblee and Bassett (1966; fault “B” of Hart, 1987a). (See Figure 2a & 2b). The Lavic Lake fault (unnamed at the time) was not evaluated, other than noting that mapping by Dibblee (1966, 1967b, 1967c) and Morton and others (1980) indicated questionable Pleistocene or Holocene activity near the junction with the Bullion fault and that Pleistocene deposits were faulted farther north. Hart (1987a) judged the southernmost expression [of the Lavic Lake fault] to be erosional. Bryant (1986, 1988) and Hart (1987b) evaluated the Mesquite Lake fault, and zoned a portion of it in the Deadman Lake SE quadrangle (Figure 2b) but did not extend the zoning into the Deadman Lake SW quadrangle, judging this northwestern extension to be not well defined.

RUPTURE SYNOPSIS

Surface rupture from the Hector Mine earthquake extended bilaterally northwest and south from the northern Bullion Mountains (Figure 1). As in the 1992 Landers earthquake, fault rupture followed pre-existing northwest-trending faults, but tended to step right to accommodate a more NNW-trend compared to the older faults. Principal rupture, with up to 5.2 m dextral slip, occurred along a partially mapped unnamed fault, now called the Lavic Lake fault (Figure 2a; Hector Mine Earthquake Geologic Working Group, 1999; Treiman and others, 2002).

Southward the rupture merged into the southern portion of the Bullion fault zone (Figure 2b). Several south trending splays of the Lavic Lake fault probably play a part in the transfer of slip between the two faults, although the more northerly splays did not have continuous rupture in the 1999 earthquake. Rupture continued southeast along the Bullion fault zone, including both the East and West Bullion faults (Figure 2b). Rupture also stepped right across Gypsum Ridge to what is probably the northern extension of the Mesquite Lake fault (informally called the “Murphy” fault or strand). Displacement along the East and West Bullion faults died out north of Deadman Lake. Displacement along the “Murphy” fault may have extended (discontinuously) to Deadman Lake, based on observation 1½ years later of slightly weathered open-fissures in the dry lake bed (Plate 8, locality 8d). Additional surface rupture, possibly subsequent to the earthquake, was also recently observed (2/7/01) at the southern end of the dry lakebed (Plate 9, locality 9a). A possibly failed right-step to another fault (unnamed fault of Dibblee, 1967b; fault “A” of Bortugno, 1987), is suggested by minor dextral displacement (up to 4mm) within a linear zone of discontinuous fractures (Plate 8, locality 8e). Bortugno (1987) suggested that this fault may be a continuation of the West Calico fault.

Within the northern Bullion Mountains (Plate 5) rupture was fairly well constrained to a single fault (the Lavic Lake fault), although one significant zone of faulting splayed out to the northeast and north. This “splay” zone included thrust faulting and overlies the main northerly trend of aftershocks (see discussion of seismicity).

Northwestward into the Lavic Lake basin the rupture followed one main fault zone that broadened slightly as it ruptured across an area of coalesced alluvial fans and exhibited minor left-steps as it crossed the Lavic Lake playa (Plate 4). Slip diminished rapidly north of Lavic Lake, with some slip distributed along several north-trending splays while faulting stepped left and died out into the southern margin of the Pisgah Crater lava fields (Plate 3). A short northeast-trending zone of left-lateral ground rupture was mapped near the Hector Mine (Plate 1, locality 1a), a little over 5.5 km northwest of the last rupture within the Pisgah lava flows. Some displacement also occurred on a fault to the east within the lava fields north of Lavic Lake (Plate 4, locality 4b), and was perhaps co-seismic, although it was not observed until nearly 1½ years after the earthquake. Possibly significant ground fracturing also occurred to the northeast, along the aftershock trend, north of Highway 40 (Plates 2 and 4).

SEISMICITY (Figure 3)

Seismicity associated with the 1999 earthquake defined a tri-lateral rupture zone in the sub-surface (Haukkson and others, 2002; Ji and others, 2002). Primary rupture (sub-surface) trended N06°W/S06°E with an additional rupture segment extending NNW. Surface rupture occurred southward from the epicentral area and along the NNW zone. Aftershocks continued for several months after the earthquake, particularly in the northerly portion of the rupture zone and farther north, with a notable gap in the northern area. Field checks through the end of November 1999 did not find any indication of additional rupture or ground cracking in the area adjacent to Highway 40. To the southeast the aftershock pattern particularly highlighted the trend of the East Bullion fault where surface rupture was mapped, and farther south where rupture might be inferred based on Interferometric Synthetic Aperture Radar (InSAR) data (see below) and aerial photography.

AERIAL PHOTO INTERPRETATION *– based on pre-earthquake imagery (see list of photos used at the end of this evaluation) -- interpretation limited to vicinity (~1500 m) of 1999 rupture zones and area of fractures north of Highway 40 (see Plates 1-9) and prominent fault on Morgans Well quadrangle (Plate 10).*

Lavic Lake fault (Plates 3-7)

In aerial photography from 1952-1953 (USDA) the Lavic Lake fault is evident as a bedrock fault through much of its Bullion Mountains section (Plate 5). Tonal and vegetational lineaments indicate probable gouge zones and tonal or vegetation contrasts mark juxtaposed lithologies. Discordant bedrock structure is also indicated by contrasting tonal and textural patterns across the fault in several localities. The fault and its splays are marked more sparingly by geomorphic features, including sidehill benches, eroded scarps, linear breaks-in-slope, linear drainages, aligned saddles, contrasts in erosional texture and truncated geomorphic features (such as ridges, ridge spurs and eroded remnants of older alluvial surfaces). Most of these indications fall into the category of fault-line features, which may have developed because a fault in the bedrock has created clay gouge (retaining or ponding groundwater) and has juxtaposed lithologies of contrasting characteristics (resulting in different vegetation or erosional patterns). However, some features, most importantly the scarps and sidehill benches, are more readily explainable by tectonic offset of the ground surface. Features of this nature are most apparent near the junction of the Lavic Lake fault with the Bullion fault, but also appear sporadically along the fault to the north, as well as along one of its major splays linking it to the Bullion fault. Some scarps observed appear as sub-linear margins to remnants of older alluvial surfaces (localities 5a or 6a), and the degree of erosion, including gullying and rounding, indicates a probable pre-Holocene age. There was a notable lack of offset drainages [as visible in aerial photos] along the Lavic Lake fault (both the larger drainages and minor gullies), and many older alluvial surfaces showed no fault expression. A notable exception, at locality 5c, is described under "POST-EARTHQUAKE FIELD OBSERVATIONS".

North of the Bullion Mountains the fault had extremely limited pre-earthquake expression (in aerial photos), mostly recognizable only in hindsight, although a scarp and parallel trough across a Pleistocene lava flow (from Sunshine crater) and adjacent pressure ridge at Lavic Lake provided evidence for Quaternary, but not necessarily Holocene, movement (locality 4d and Photo 1).

Fault expression, tonal or geomorphic, was lacking in the modern alluvial fan and channel deposits and only sparingly expressed in some remnants of older alluvial surfaces, such as at localities 5a and 6a, mentioned above. There were linear vegetation patterns in the dry bed of Lavic Lake, some of which ultimately proved to be along the fault rupture, but many other lineaments were not. Desiccation cracks probably controlled many of these vegetation lineaments. There was no evidence that this fault previously extended into the Pisgah Crater lava flows.

Bullion fault (plates 5-9)

The Bullion fault zone is apparent in the 1952/1953 aerial photography, except across some of the younger alluvial areas. Much of the fault was previously zoned, based largely on its well-defined and youthful character in aerial photography (Hart, 1987a). The fault is characterized in the current rupture zone by tonal and geomorphic expression as indicated on Plates 5-8. Topographic features include several right-deflected drainages, back-facing scarps and other instances of truncated geomorphic surfaces suggesting more recent (Holocene) displacement than is apparent on the Lavic Lake fault. The East Bullion fault has no expression immediately south of the portion that recently ruptured, although there are some indications of a possible parallel Quaternary fault within the dissected mountain front to the east (localities 7a-7c). The West Bullion fault had some prior expression, also limited to the section that ruptured in 1999. Both strands (as inferred by Dibblee, 1967b) also have very limited topographic expression within the Deadman Lake SE quadrangle (Plate 9).

Mesquite Lake fault (plates 7-9)

The northernmost portion of the Mesquite Lake fault ("Murphy" fault – Plates 7 & 8), to the west and southwest of Gypsum Ridge, had a few tonal indications of its location and also had scattered geomorphic indicators of at least Pleistocene displacement (Morton and others, 1980; also this study). Geomorphic features included the fault-bounded margin of an older fan surface (locality 7d) and truncated ridges (locality 8b). Adjacent to and south of Deadman Lake (Plates 8 & 9) scattered tonal and weak topographic lineaments along the fault (Morton and others, 1980; Hart, 1987a,b), although somewhat widespread, provide support for the significance of the InSAR lineaments (discussed below). A few of the lineaments of Morton and others (1980) were noted to be possibly lithologically controlled (Hart, 1987b). Stronger expression to the south was part of the basis for including that portion in an Earthquake Fault Zone (Bryant, 1986; Hart, 1987b).

Other faults

The northeast-trending sinistral fault, northeast of the Hector Mine (Plate 1), lacked geomorphic expression on the pre-rupture USDA photography.

The unnamed fault north of Lavic Lake mapped by Wise (1969) is clearly visible and mappable on the USDA photography. It is expressed by a series of principally west-facing scarps and tonal lineaments across the basalt flows of Pisgah crater. (See Plate 4)

A northern extension of fault "A" of Bortugno (1987; unnamed fault of Dibblee, 1967b) is recognizable by several apparently fault-bounded eroded blocks of uplifted older (Pleistocene?) sediments (Morton and others, 1980; also this study, Plate 8).

An unnamed fault on the Morgans Well quadrangle (Plate 10), previously mapped by Dibblee (1967a), has evident Quaternary displacement, as indicated by scarps and deflected drainages within alluvial fan units. At locality 10a a channel incised into an older alluvial fan is offset and partially blocked by an upstream-facing scarp in the older fan.

Other areas where there was reported ground cracking (see below) were also interpreted in the USDA imagery. Evidence of possible prior Quaternary offset along a fault north of the Lavic siding (AT&SFRR along Highway 40) includes a scarp that is cut by two antecedent drainages as well as a distinct vegetation contrast (Plate 2). No indications of prior faulting were seen at the locale of the Pisgah cone fractures (Plates 1, 3 & 4). Fault "B" of Hart (1987a; Plate 1 herein) was previously discussed in that report. It was recognized by broad scarps, tonal lineaments, a sidehill bench, deflected drainages and a scarp in the Pisgah basalt flows. Fault "B" was not re-interpreted for this study.

AERIAL PHOTO INTERPRETATION – post-earthquake imagery (see list of photos used at the end of this evaluation) see Plates 4-8

Post-earthquake aerial photography clearly shows most of the main fault rupture and much of the subsidiary rupture. Aerial photographs were taken at an approximate scale of 1:10,000 for most of the surface rupture and for part of the northern rupture at a scale of 1:3000. Ground rupture with as little as 5-10 centimeters displacement was locally visible in the photography as inspected with a binocular microscope (10X). Identifiable ground rupture was scribed onto clear film overlays, and the overlays were scanned and registered to digital ortho-photographic images (pre-earthquake) of the marine base [courtesy of the U.S. MCAGCC, Geospatial Information and Services/Remote Sensing Lab] by matching unique features visible in both pre- and post-earthquake imagery. Ground ruptures were then digitized from the scanned overlays into a GIS database. Faults mapped in this manner are plotted in red on the plates. Photo interpretation and digitizing of recent rupture was done by the author and W.A. Bryant.

Not all rupture was visible, for a number of reasons: 1) some areas were in shadow; 2) some rupture of low relief did not cast significant shadows; 3) some rupture was too fine for the image resolution; 4) rupture distributed within coarse alluvial fan deposits often paralleled (and was masked by) bar and swale topography; 5) some rupture zones were not covered by post-earthquake imagery.

Most of the interpreted rupture is not discussed here as it is well represented on Plates 4-8 and corroborated by direct field observation. One area requiring further comment, though, lies along the southeasterly projection of the East Bullion fault (Plate 8). This area was not closely interpreted nor field checked immediately after the earthquake. However, subsequent InSAR interpretation (Simons and others, 2000) strongly indicated that rupture had occurred at or near the ground surface. Close inspection of the post-earthquake imagery does not reveal evident fractures, but a distributed series of discontinuous, subparallel linear tonal highlights may indicate subtle east-facing scarps in this early-morning, low-sun-angle imagery (locality 8a). This zone spreads across the width of the InSAR lineament and it is not possible to definitively say the observed highlights are not vehicle tracks or other artifacts. Field mapping 1½ years later was unable to confirm rupture in this area of shifting aeolian deposits.

POST-EARTHQUAKE FIELD OBSERVATIONS

Field observations served to fill in fault rupture not identifiable on the post-earthquake aerial photography and to quantify co-seismic slip on the faults. A representative sampling of field measurements on Plates 1-8 indicates measured slip. Fault rupture mapped on the basis of field work alone (without aerial photo identification) are plotted in magenta, as distinct from those faults in red that were identified in the post-earthquake photography. Other than in the northern lava fields (Plates 3 and 4), where older aerial photography allowed accurate field location, the depiction of the field-mapped rupture may not be as accurate as those interpreted directly from the aerial photography. Fault rupture location was aided by the use of GPS receivers, but most of this field work was done before the Department of Defense terminated selective availability (SA). SA artificially introduced an error of as much as 100 m.

Most of the fault rupture was fairly well-constrained to an identifiable main fault or zone of faults. Exceptions included the southern stepover zones between the Lavic Lake and Bullion faults (Plates 5 and 6), from the East Bullion fault to the West Bullion fault (Plate 7), and from the West Bullion fault to the Mesquite Lake fault (“Murphy” fault strand; Plates 7 and 8). In some of the coarse alluvial fan areas (particularly just north of the Bullion Mountains; Plate 5) surface rupture was not fully identified in aerial photography and too diffuse to map accurately (locality 5b). Even in the field, ground rupture and moletracks across these fans were often difficult to distinguish from stream bank failures and seismically shaken gravel bars. Rupture was also very distributive and discontinuous at the northern terminus of the main rupture, northwest of Lavic Lake where field mapping was necessary to record fine rupture and systematic cracking too small for the aerial photo image resolution. It is likely that additional small-scale ground fracturing occurred beyond what was mapped.

Within the Bullion Mountains, field mapping filled in areas obscured by shadows in the imagery, provided slip data and allowed better evaluation of evidence for prior events. At locality 5c, a pre-existing graben, including a small east-facing scarp, had renewed rupture in 1999. The 1999 rupture scarp here is approximately 50 cm high, whereas the total scarp height at this location is about 1 m. Old alluvial fan remnants along the east side of the graben were dextrally offset about 4-4.5 m in the 1999 event. Total dextral offset of this alluvial-fan remnant is about 9-9.5 m, which, combined with the scarp height, implies that the penultimate event was similar in displacement to the 1999 earthquake.

Field mapping was necessary in the southern end of the fault zone where stepovers extended ground rupture beyond the coverage of the post-earthquake imagery and where rupture was too fine to see in the photos (Plates 7 and 8). As at the northern end of the fault zone, displacement diminished to non-measurable levels, but continued as linear zones of fracturing, en-echelon fracture patterns and small-scale compressive stepovers which documented a persistent, if miniscule, right-lateral strain. Rupture along the “Murphy” fault strand and the northern extension of fault “A” was entirely outside the post-earthquake aerial photo coverage and was mapped with the aid of GPS receivers, topographic base map (marginal use in low-relief terrain) and 1950’s USDA aerial photography. The “Murphy” strand of the Mesquite Lake fault (Plates 7 and 8) was well-expressed by a pair of continuous fractures (with a graben between) at its best and diminished to less continuous en echelon fractures at the north and south ends of the rupture. A portion of the northern segment of the fault (locality 7d) was observed to bound a slightly elevated and dissected older fan surface that is also visible in the USDA photography. At least one fault (and probably others) splayed off to the north and northeast (localities 7e & 8c), probably accommodating slip transfer from the West Bullion fault. These splays were generally more extensional than the main fault trend.

The northern extension of fault “A” (Plate 8) was expressed as a weak zone of minor *en echelon* fractures with a maximum of 4 mm dextral slip. Ground rupture may have extended farther south, but was not followed.

Study of InSAR interpretation (see below) led to additional field reconnaissance in February 2001 to explore ruptures along the East and West Bullion faults and the Mesquite Lake fault that were not identified in the initial field effort. Rupture trace location was based principally on hand-held GPS receivers (post-selective availability accuracy of ~2.5 m). The full extent of surface rupture on these faults was probably no longer preserved, due to flooding and shifting of extensive aeolian sand deposits in the year and a half since the earthquake. Rupture on the East Bullion fault (Plate 7) was somewhat degraded, as would be expected for 1½-year old features, and was judged to probably have been co-seismic. Vertical separations were apparent (up to 0.5m), although some of this may have been due to graben formation between en echelon fault strands. Lateral displacement was still observable at some locations, up to 70 cm right lateral. At the southern end of the mapped rupture the fractures were slightly more diffuse, and farther south were probably obscured (if present) by shifting aeolian sand. Several additional traverses across the eastern InSAR lineament failed to identify further ground rupture.

The southernmost rupture on the West Bullion fault (Plate 8) was no longer apparent, having been almost entirely obliterated by flash-flooding or covered by aeolian sand. One very subtle scarp was observed and identified only because it was visible in the post-earthquake photography.

The previously unexplored InSAR lineaments projecting toward the Mesquite Lake fault (Plates 8 and 9) were almost entirely within the bed of Deadman Lake or along the dune areas on its western “shore”. It was not expected to find much evidence of surface rupture due to flooding and aeolian activity in the 1½ years since the earthquake. In spite of the time and weather, one prominent 40m-long fissure was mapped on the playa surface (locality 8d). Distinct from desiccation cracks, this fissure was both more open and more continuous than the otherwise pervasive mud cracks. Furthermore, mudcracks in a somewhat linear zone, north and south of this feature, were notably more open than elsewhere. It is not known if the fissure resulted from tectonic displacement or secondary shaking phenomena in the lake beds (e.g. liquefaction). The fissure had a weathered appearance commensurate with having been submerged or otherwise modified by seasonal runoff. A west-northwest trending zone of normal (extensional) fractures at the southern end of the dry lake (Plate 9, locality 9a) appeared to be much fresher than other fractures mapped, and their formation may post-date the earthquake.

A pre-existing fault across the southern Pisgah crater lava flows (Plate 4, locality 4b) was called to our attention by Art Sylvester (originally mapped by Wise, 1969). Inspection of this feature in February 2001 found it to be expressed by a discrete zone of disturbance across the ~20 ka flows. Varying from a single trace to en echelon and parallel faults bounding local graben, the fault was characterized by a fissure or fissures, either open or filled with toppled and stirred rubble. Vertical separations (pre-earthquake) were mostly east-side up. One flat surfaced flow displayed a cumulative vertical offset of 18 cm. Within the fissure associated with this offset were multiple scuff or abrasion marks where one side of the fissure had impacted the other side. Fresh rock dust indicated the most recent movement. Varying degrees of patina on older abrasions indicated at least two prior events. Other evidence of very recent activity included fresh fracturing of aeolian silt deposits in hollows and fissures and freshly stirred rubble within the fault fissure. The fresh stirring was indicated by the exposure of the reddish undersides of angular cobbles within the fissure. The indications of recent movement were localized to the observed fault zone and did not appear in other fissures, collapsed lava tubes or the more northerly portions of the fault zone.

Follow-up on reported ground fractures beyond the principal rupture

Ground fracturing was reported in four areas north of the Marine Corps base and was field checked. North of the Hector Mine a northeast-trending zone of fractures was reported and was found to have up to 3.5 cm of left-lateral displacement (Plate 1, locality 1a). The 650 m-long zone of right-stepping en echelon fractures re-occupied and extended an older zone of eroded en echelon fissures. Plant growth within the fissures indicated that these older features clearly pre-dated the 1999 earthquake.

Fractures were also reported within the right-of-way for several major gas lines crossing the area north and south of Highway 40 (Figure 2a). Fractures along some of the pipelines were parallel to the pipes and most likely related to settlement or other shaking effects within pipeline trench backfill. However, in two areas there were zones of cracks extending orthogonal to the pipe trend. There were no reported pipeline ruptures. In the SE corner of the Hector quadrangle (Plate 1), south of the highway, fracturing with no measurable displacement crossed a gas line and appeared to have followed along portions of a previously zoned fault segment (fault B of Hart, 1987a – see Plate 1)). To the east, within the southern portion of the Sleeping Beauty quadrangle and northernmost margin of the Lavic Lake quadrangle, two parallel zones of fractures crossed at least two gas lines (Plates 2 & 4). These two fracture zones roughly followed along the margins of a gentle south-draining linear valley. Although a fault had not been previously mapped in this location, it was apparent from aerial photo interpretation that a north-south-trending bedrock fault does lie in close proximity to the western of the two fractures. The western fracture zone had a distinct left-stepping en echelon pattern along part of its length and seemed to roughly parallel a contrast in both lithology and vegetation. The principal contrast was that between cobbly fanglomerate to the west and windblown dune sand to the east, with a relatively linear contact between them. The vegetation contrast is attributed to the lithologic differences. Both the east and west zones had distinct left-stepping fractures patterns and vertical displacements (down toward the valley) of up to 7 cm, but more commonly less than 4 cm. Lateral offset was not detectable. Within several shallow valleys in this area the exposed edge of the fanglomerate layer seemed to hold up low scarps that were not necessarily linear. Other zones of fractures, not aligned with the bedrock fault, were observed following the margins of several smaller swales to the north that contained wind-blown sand deposits. South of the highway (Lavic Lake quadrangle) there were a few other scattered observations of limited ground fracturing, but no lateral displacement was measured.

The fourth area of reported fracturing was along the eastern and northwestern flanks of the Pisgah crater cinder cone (northwest corner of Plate 4, locality 4a). The eastern fracture zone was irregular in outcrop pattern (Figure 4) with east-facing scarps up to 80 cm high (Sylvester, Burmeister and Wise, 2002). The scarps give the initial impression of resulting from normal separation, but had, in most locations, abundant debris below the scarp suggesting collapse of an overhang. Close inspection of a few localities showed a loose layer of gravelly cinder, parallel to the slope, exposed near the base of the scarp. In the central portion of the fracture zone a tread and riser slope morphology accompanied two sub-parallel zones of surface disruption, each zone occurring near the top of a riser. At the southern end of the fracture zone the upslope side of the fault was deformed, as if it had pushed up over the downslope side, but to the north this style of deformation was not evident. The fracture pattern locally "veed" westward, also suggesting a thrust or landslide mechanism. On the north side of the cone a linear zone of north-trending fractures, both above and at the toe of sub-parallel slopes, was observed. It coincided, in part, with a quarry free-face. Top-of slope fractures were generally tensional, and also were somewhat en echelon, whereas toe-of-slope deformation appeared largely compressional.

InSAR DATA

Interpretation of Interferometric Synthetic Aperture Radar (InSAR) images by various workers has provided additional insight into the ground deformation accompanying and following the Hector Mine earthquake. Of particular use is an InSAR image by Simons and others (2000, 2002). Their processing of InSAR data from the European Space Agency indicates linear zones of surface deformation developing within the period from September 15 to October 20, 1999, as indicated by zones of "de-correlation". The linear zones of high de-correlation in the interpretive image by Simons and others (2000) are striking in their correspondence to the principal (and even much of the minor) ground rupture associated with the Hector Mine Earthquake (Figure 5). In most localities the surface faulting appears to correspond to the eastern edge of the decorrelation zones. Broad de-correlation also occurs in some areas of the Bullion Mountains and between the Lavic Lake fault and the northeastern rupture zone. Additional linear zones of de-correlation occur sub-parallel to (and west of) the inferred concealed trace of the East Bullion fault (after Dibblee, 1967b) and as a connecting lineament between the "Murphy" fault and the Mesquite Lake fault.

The broad zone of de-correlation in and northwest of the epicentral area is enigmatic, but may be due to a combination of rockslides and landslides in the northern Bullion Mountains as well as disturbed ground due to the inferred high ground accelerations in this area. The distinct zone of de-correlation parallel to the East Bullion fault, and subsequent verification of ground rupture, indicates that the fault probably lies west of its inferred location as mapped by Dibblee (1967b) and that displacement may have occurred along a considerable length of this fault. The zone of de-correlation along the West Bullion fault was also corroborated by surface rupture. Minor surface fractures and displacement along the northern projection of the Mesquite Fault support the tectonic significance of this InSAR feature, as well. At the scale of InSAR data interpretation by Simons and others (2000, 2002) the lines of decorrelation are not precise enough to locate a fault on the ground for zoning purposes. However, they are sufficient to demonstrate the general location and continuity of faults that are corroborated by other data.

DISCUSSION AND CONCLUSIONS

The principal zone of ground rupture clearly demonstrated the activity of the Lavic Lake fault, as well as the Bullion fault and its southern strands, and the northern ("Murphy" fault) portion of the Mesquite Lake fault. Field observations also support the active designation of fault "A" (of Bortugno, 1987). The pattern of rupture also seems to demonstrate the current tendency for older fault zones within this portion of the Mojave Desert to partially rupture and link up so as to present a more north-northwesterly rupture trend.

The Lavic Lake fault had some evidence of prior Quaternary movement, although not evidently Holocene. Principal indicators of prior Quaternary surface rupture were saddles and scarps within the northern Bullion Mountains. Prior fault rupture was suggested, within the Lavic Lake basin, by a pressure ridge and scarp in Sunshine Crater basalt (locality 4d, see Photo 1), and a possibly depressed area of the dry lakebed, west of the fault (locality 4c). This possible depression was indicated by the presence of several pre-existing westward draining gullies that appeared to be incised, east of the fault. 1999 displacement occurred along the east margin of this depression and InSAR data showed continued post-seismic subsidence in this vicinity (Jacobs and others, 2002).

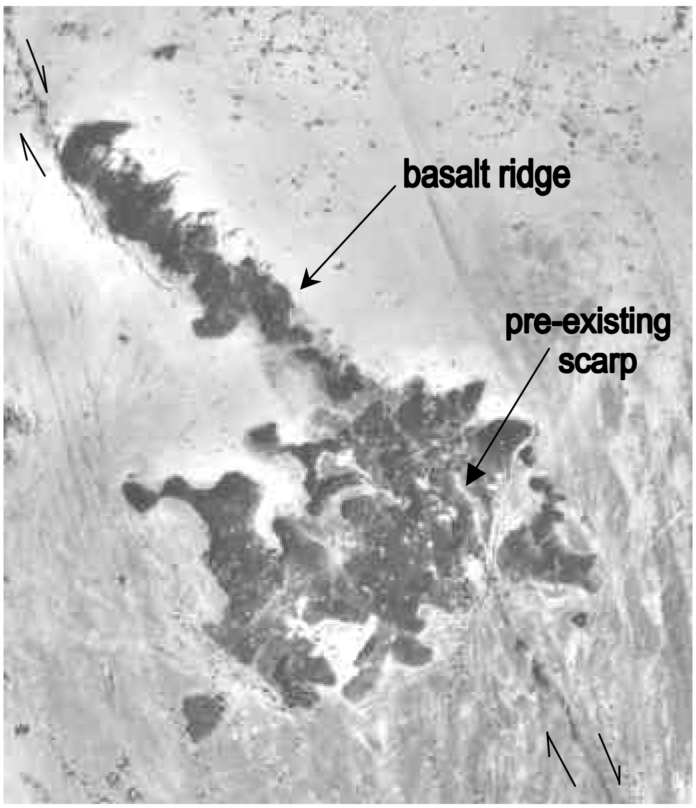

Photo 1 - outlier of Sunshine Peak basalt with prominent northwest-trending pressure ridge or ridge of extruded basalt *(from photo by I.K. Curtis, 1999 - leg 7, frame 5)*.

1999 rupture into the southern margin of the Pisgah Crater lava flows appears to have been the first surface rupture since these flows occurred, ~20,000 years ago (age based on unpublished data from D. Champion, USGS). It is possible that prior rupture did occur in the subsurface but did not propagate upward through the flows. There is a structural implication that the eruptive events that produced the Pisgah cinder cone may have found their way to the surface along the Lavic Lake fault. The hardened intrusive plug may be currently blocking further propagation of rupture along this fault.

Perhaps as a result of this inferred blockage there was subsurface rupture (Figure 3) and limited surface rupture (Plate 5) extending northward from the epicentral region of the 1999 Hector Mine earthquake (east and southeast of Pisgah Crater). This appears to be circumventing the blockage of the Pisgah cone. Surface rupture was complex in the epicentral area, including both dextral and thrust components. Although limited tonal and geomorphic features correspond to the recent rupture, it is difficult to try to project this fault zone beyond the limits of the historic surface rupture.

The Lavic Lake fault merges southward into the Bullion fault across several connecting splays, only some of which had displacement in the recent earthquake. The westernmost of these splays only had historic displacement in its northernmost portion, adjacent to the main trace of the Lavic Lake fault (Plate 5). However, the southern portion of this splay has abundant geomorphic evidence of activity that may be related to the penultimate event. Recent post-earthquake trench studies (Lindvall and others, 2001) suggest that although the Bullion fault has had multiple late Holocene displacements, the Lavic Lake fault, south of a major drainage divide (Plate 5, sec.9, T5N, R7E), had not broken (until the recent event) in tens of thousands of years. One interpretation is that the penultimate event may have bypassed the trench site by rupturing the westernmost splay to connect the Lavic Lake and Bullion faults.

The Bullion fault has clear evidence of Holocene displacement along most of its main trace. This earthquake confirmed the activity of the central portion of the fault and further demonstrated the activity of the East and West Bullion faults to the southeast. The East Bullion fault had been previously inferred as a range bounding fault along the southwestern margin of the Bullion Mountains (Dibblee, 1967b). InSAR data (Simons and others, 2000), as partially confirmed by field mapping and aftershock distribution and aerial photo interpretation (post earthquake imagery), indicate that an active fault lies southwest of the range front. Since the previously mapped trace was entirely concealed we interpret that the East Bullion fault probably corresponds to the zone of recent activity and should be plotted outboard of the range front. Recent surface rupture clearly occurred in a well-defined zone along at least part of the InSAR lineament, but more diffuse indications of possible ground disturbance in the southern portion of the lineament (locality 8a) may indicate a broader zone of distributed deformation rather than discrete ground rupture.

The West Bullion fault was marked by historic rupture that essentially corresponded to the entire InSAR lineament at this location. There is no data on which to base a further active extension of this fault.

The Mesquite Lake fault appears to connect to the “Murphy” fault west of Gypsum Ridge, based on the InSAR interpretation of Simons and others (2000), aerial photo lineaments (Morton and others, 1980; Hart, 1987b) and trenching data of Rasmussen (1983, cited by Hart, 1987b). InSAR interpretation, and aerial photo lineaments (plates 8 & 9) suggest that the Deadman Lake structural basin may have formed in an extensional right-step between the northern (“Murphy”) strand and the main strand of the Mesquite Lake fault. Very localized (or locally preserved) fissuring and faulting in and adjacent to Deadman Lake fit this extensional model.

The northward extension of Fault “A” (Plate 8) is indicated by truncated geologic structures, scarps and tonal lineaments, and the minor displacement at the northern end of this zone suggests that it is still active in accommodating regional strain.

Fault “B” (Plate 1) demonstrated minor triggered displacement within a small stepover, as indicated by the en echelon pattern of the fractures.

The fault shown on the Morgans Well quadrangle (Plate 10) has strong geomorphic expression indicating its location and has dextrally offset several drainages. Quaternary activity is demonstrated by its effects on several older alluvial deposits and recency is suggested by its relatively better expression as compared to the Lavic Lake fault.

Sinistral faulting north of Hector Mine (Plate 1) appears to have recurred along a pre-existing fault, as indicated by the weathered en echelon linear depressions observed in the field. Based on the degree of weathering these possibly in-filled fault fissures may have developed as a result of the 1992 Landers earthquake.

Fracturing north of the Lavic overcrossing (Plates 2&4) appears to correspond to a pre-existing fault. The nearby train derailment, other fracturing, and settlement affecting man made fills and colonies of burrowing animals indicate that there were perhaps unusually high ground accelerations in this area. However, the high ground accelerations, alone, are not sufficient to explain the en echelon pattern and direct alignment with a bedrock fault; these aspects suggest that non-measurable dextral strain occurred here in addition to the shaking.

At Pisgah Crater (Figure 4; also Plate 4, locality 4a), the zone of surface breakage included characteristics of both faulting and slope failure. Deformation (principally flattening or decrease in slope) occurred above the fractures at the southern end, as if the ground had ramped up over the lower slope. The tread and riser morphology to the north was on a much larger scale, and could have resulted from either upramping failure planes producing the treads or, conversely, two faults offsetting a gentler slope creating the risers/scarps. Either process has occurred more than once, as indicated by prior dissection of the tread surfaces. The most recent surface rupture was located well up the riser face. Shallow drainages across the more northerly part of the rupture gave the impression of having been offset vertically. The irregular yet broadly arcuate outcrop pattern of the rupture requires either a very irregular high-angle fault surface (normal or reverse, but not strike-slip) or a very low angle failure surface, perhaps even sub-parallel to the slope. The fresh talus debris below the scarps and “veeing” of the fracture traces indicate a dip to the west and collapse of an overhang. The limitation of the fracture zone entirely to the cinder slopes further indicates slope failure as the likely mechanism rather than faulting. The presumably slope-parallel layers of tephra might be expected to provide suitable layers of loose cinders to allow slope failure. Arguing against the fault hypothesis is the rupture pattern, which wraps around the cone, roughly parallel to the slope contours, and the lack of rupture away from the cone. Furthermore, if tectonic fault rupture had occurred here we would have expected seismicity, rather than a seismic gap at this location. The center of the solidified magma body seems the least likely locale for limited fault rupture to take place.

The fracture zone on the north side of the Pisgah Crater (Figure 4, Plates 1 and 3) was perhaps more likely to be at least fault related. In older (1952) aerial photos it looks as if there may be a fault zone at this locality. Much of what we see now looks like slumping, particularly adjacent to the quarry, and farther northwest one could also argue for slope failure, but the correspondence with the older structure is suggestive of shaking focused along an old disparity. On the negative side (for fault association) there was no cracking where this zone projected across the low-lying northeast-trending alluvial area just north of this cinder lobe.

RECOMMENDATIONS (Plates 1-10) - faults to be zoned indicated by gray highlight

New Earthquake Fault Zones should be established to encompass the Lavic Lake fault and related splays on the Sunshine Peak, Lavic Lake, Lavic SE, Hidalgo Mtn. and Deadman Lake NW quadrangles, as indicated by gray highlighting on the plates. The fault traces are based on the recent rupture mapping by Treiman and others (2002) and as presented in this FER. [Plates 3-7]

The existing Earthquake Fault Zone along the southern section of the Bullion fault (including both southern strands), on the Deadman Lake NW and Hidalgo Mtn. Quadrangles (as mapped by Hart, 1987a), should be revised to more accurately encompass the active fault traces as indicated by 1999 ground rupture as described by Treiman and others (2002) and as evaluated in this FER. The zone for the West Bullion fault should be extended to include historic rupture on the Deadman Lake SW quadrangle, as reported by Treiman and others (2002) and as discussed in this FER. [Plates 6-9]

A new Earthquake Fault Zone should be established to encompass the NE-trending fault near Hector Mine as mapped within the Hector quadrangle by Treiman and others (2002) and in this FER. [Plate 1]

A new Earthquake Fault Zone should be established to encompass the unnamed NW-trending fault of Wise (1969) east of the Lavic Lake fault and north of Lavic Lake. Fault location is refined based on aerial photo interpretation for this FER. (Lavic Lake quadrangle – Plate 4).

A new Earthquake Fault Zone should be established to encompass the unnamed NW-trending fault of Dibblee (1967a) indicated in the southwest corner of the Morgans Well quadrangle. Fault location is refined based on aerial photo interpretation for this FER. [Plate 10]

The "Murphy" fault strand of the Mesquite Lake fault, as revealed by historic ground rupture and fracturing within the Deadman Lake NW and Deadman Lake SW quadrangles (Treiman and others, 2002), should be included in a new Earthquake Fault Zone. The inferred continuation to the previously zoned Mesquite Lake fault (Hart, 1987b), within the Deadman Lake SW and Deadman Lake SE quadrangles, is based on aerial photo interpretation by Morton and others (1980) and this FER. [Plates 7-9]

The existing Earthquake Fault Zone for fault "A" of Bortugno (1987) on the Deadman Lake SW quadrangle should be extended to include historic fracturing and other evidence of the fault to the north, as mapped and interpreted by Morton and others (1980) and for this FER (also Treiman and others, 2002). [Plate 8]

Ground fracturing along fault "B" of Hart (1987a) on the Hector quadrangle (Plate 1) was within the current Earthquake Fault Zone and does not necessitate any revisions.

Ground displacements along the east flank of the Pisgah cinder cone (Sylvester and others, 2002; Treiman and others, 2002; this FER) are believed to be non-tectonic and should not be zoned. [Figure 4]

Two north-south-trending linear zones of fracturing in the Sleeping Beauty and Lavic Lake quadrangles, as mapped for this FER, are associated with a previously unmapped fault and should be included in a new Earthquake Fault Zone. [Plates 2 & 4]

12/05/02
Report reviewed
and approved.
William A. Bryant
CEG 1554

Jerome Treiman

Jerome A. Treiman
Associate Geologist
EG 1035

AERIAL PHOTOGRAPHS USED

U.S. Department of Agriculture – b/w, 9x9, 1:20,000

AXL-6K	frames 162-169	11/10/52
AXL-7K	frames 146-157	11/10/52
AXL-8K	frames 34 - 44	11/17/52
AXL-9K	frames 85 – 96	11/18/52
AXL-10K	frames 155-156	11/18/52
AXL-10K	frames 159-161	11/18/52
AXL-11K	frames 123-125	11/19/52
AXL-32K	frames 124-127	1/29/53
AXL-32K	frames 167-173	1/29/53
AXL-37K	frames 163-171	2/04/53

I.K. Curtis Aerial Surveys

USGS Lavic Lake Fault 10/18/99

Leg 1	exposures 1-95	1:10,000
Leg 2	exposures 1-37	1:10,000
Leg 3	exposures 1-17	1:10,000
Leg 4	exposures 1-18	1:10,000
Leg 5	exposures 1-20	1:10,000
Leg 6	exposures 1-21	1:10,000
Leg 7	exposures 1-36	1:10,000
Leg 8	exposures 1-31	1: 3,000

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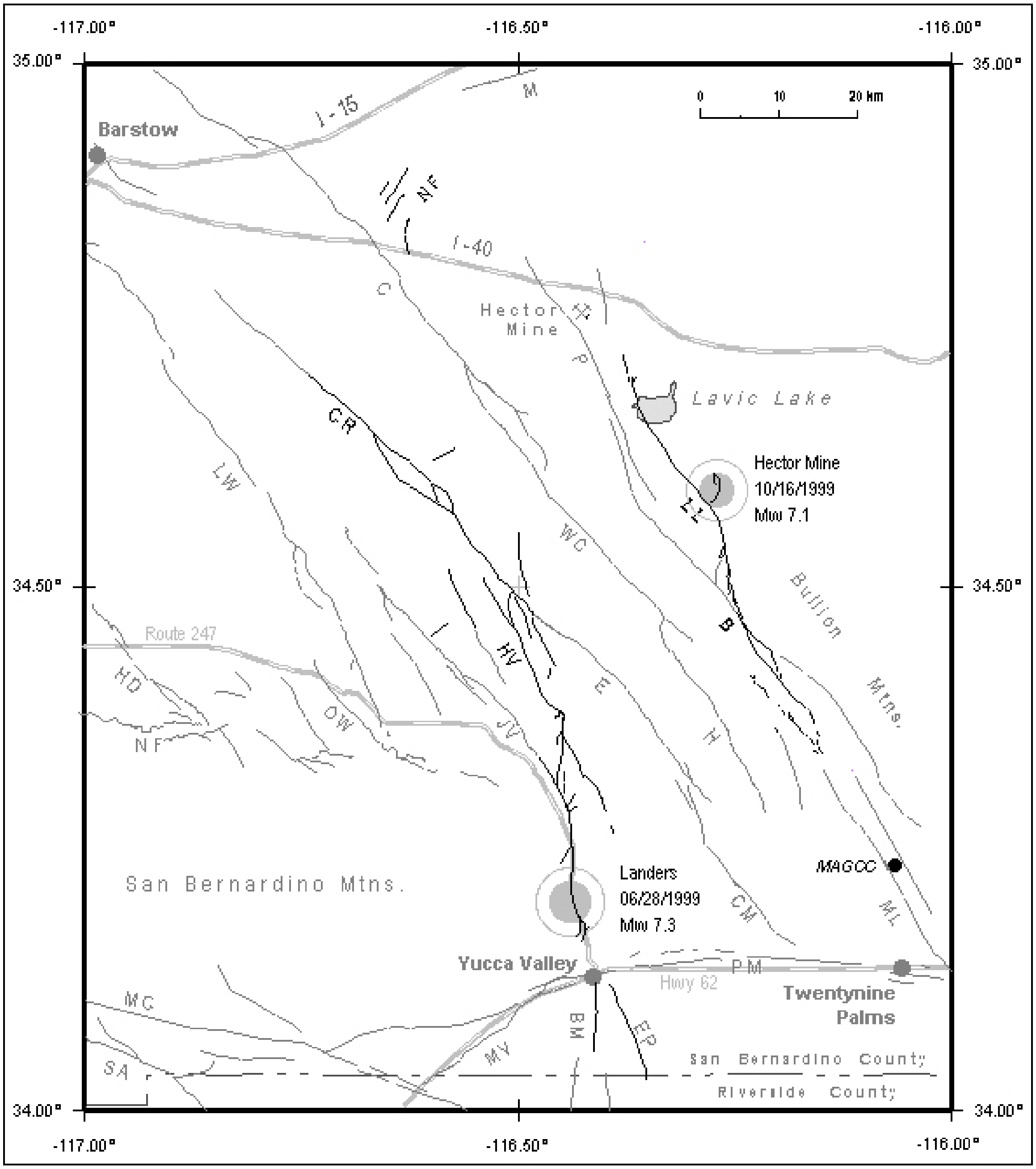

Figure 1 (FER-246) -- Location map of Mojave Desert region showing 1999 Hector Mine Earthquake epicenter and distribution of surface faulting (heavy black line). Also shown is epicenter and surface faulting from 1992 Landers Earthquake (medium black line) and other Mojave faults (gray lines).

[late-Quaternary and younger faults identified by letters: B- Bullion, BM- Burnt Mountain, C- Calico, CM-Copper Mountain, CR- Camp Rock, E- Emerson, EP- Eureka Peak, H- Hidalgo, HD- Helendale, HV-Homestead Valley, JV- Johnson Valley, LL- Lavic Lake, LW- Lenwood, M- Manix, MC- Mill Creek, ML-Mesquite Lake, MV- Morongo Valley, NF- Newberry Fracture Zone, NFF- North Frontal Fault Zone, OW-Old Woman Springs, P-Pisgah, PM- Pinto Mountain, SA- San Andreas, WC- West Calico] [MAGCC marks headquarters of the U.S. Marine Corps Air Ground Combat Center, Twentynine Palms]

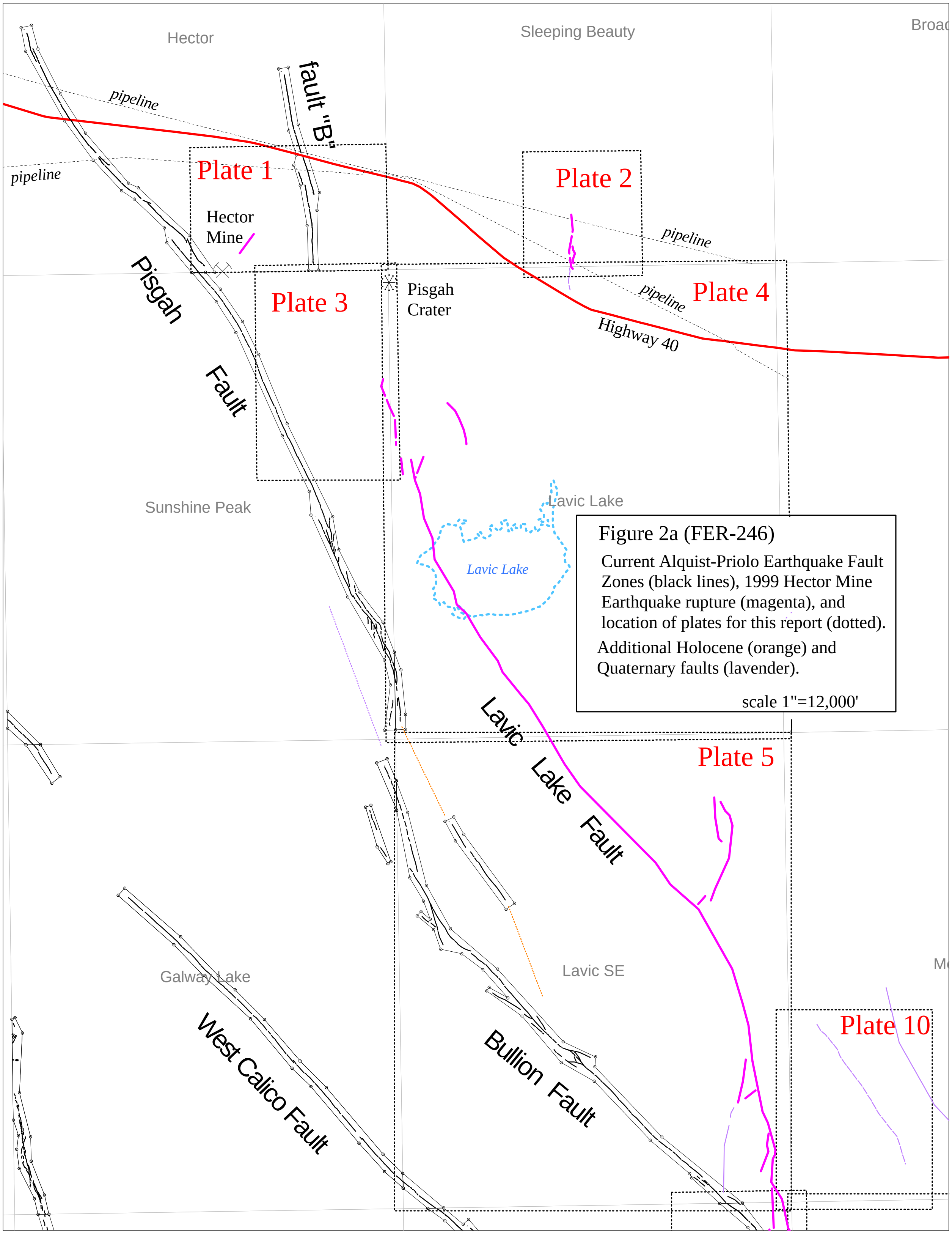

Figure 2a (FER-246)

Current Alquist-Priolo Earthquake Fault Zones (black lines), 1999 Hector Mine Earthquake rupture (magenta), and location of plates for this report (dotted).

Additional Holocene (orange) and Quaternary faults (lavender).

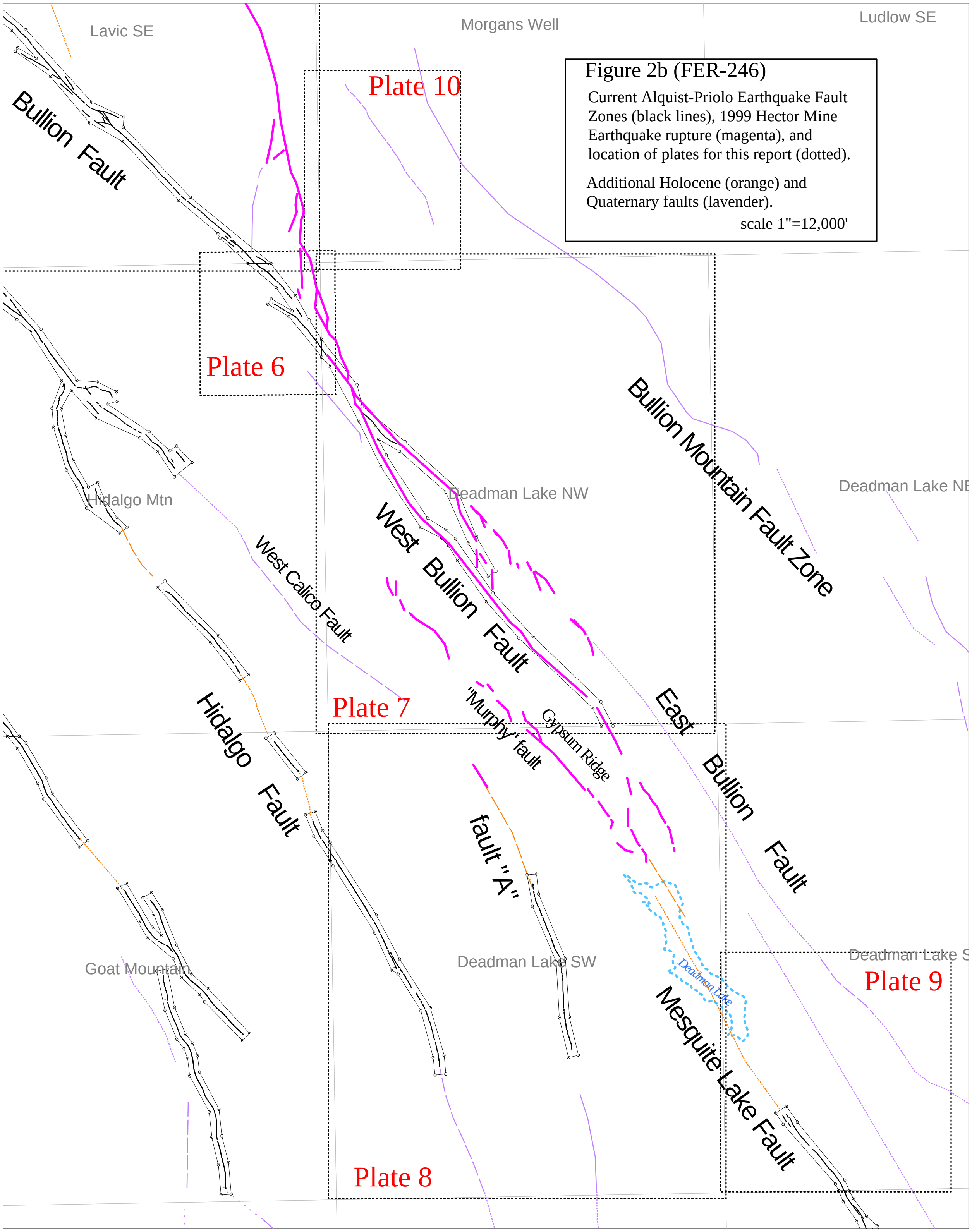
Figure 2b (FER-246)
Current Alquist-Priolo Earthquake Fault Zones (black lines), 1999 Hector Mine Earthquake rupture (magenta), and location of plates for this report (dotted).
Additional Holocene (orange) and Quaternary faults (lavender).
scale 1"=12,000'
Lavic SE
Morgans Well
Ludlow SE
Plate 10
Plate 6
Plate 7
Plate 8
Plate 9
Bullion Fault
Bullion Mountain Fault Zone
West Bullion Fault
East Bullion Fault
West Calico Fault
Hidalgo Fault
"Murphy" fault
Gypsum Ridge
fault "A"
Mesquite Lake Fault
Deadman Lake
Hidalgo Mtn
Deadman Lake NW
Deadman Lake NE
Deadman Lake SW
Deadman Lake SE
Goat Mountain

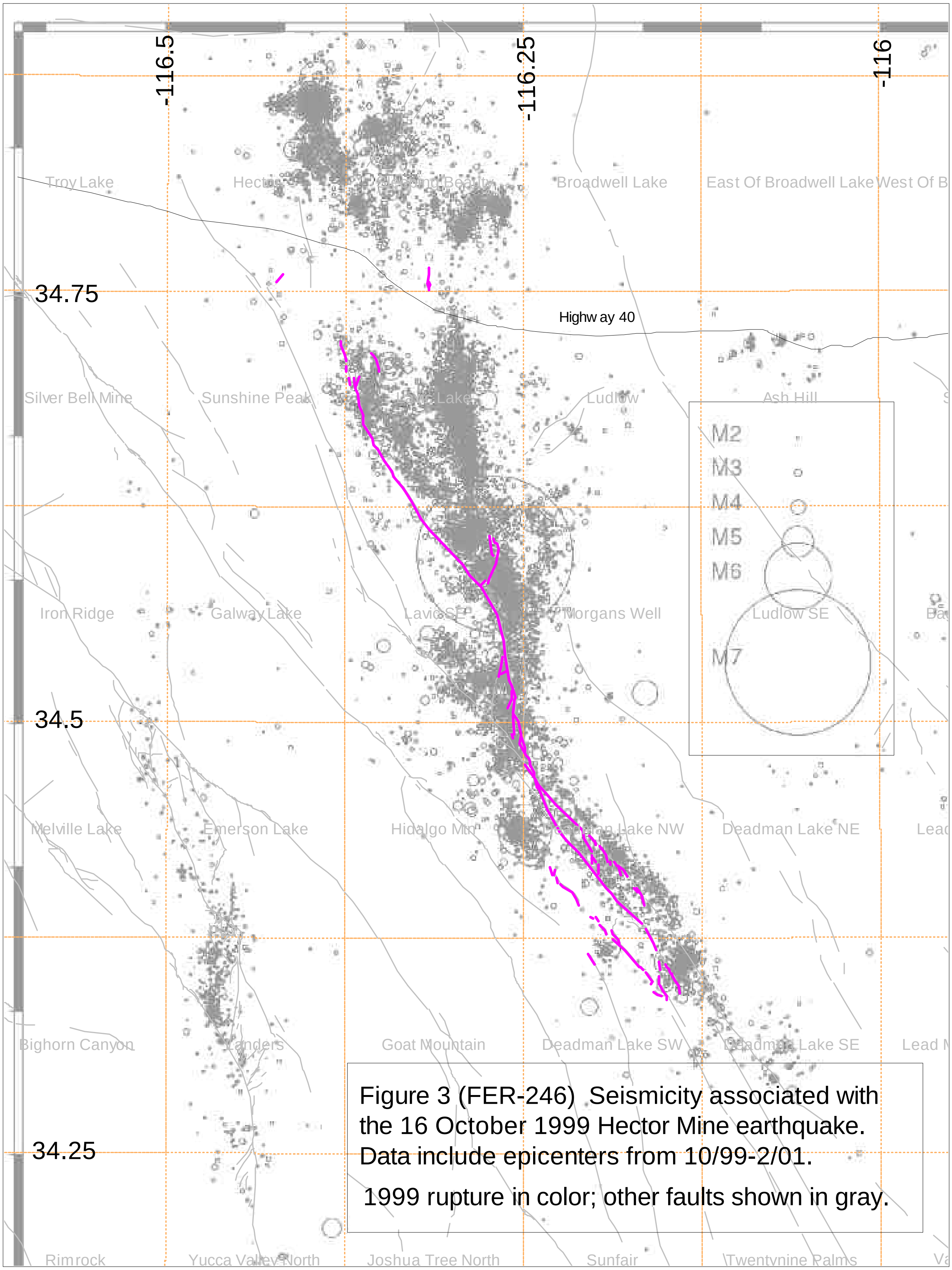

Figure 3 (FER-246) Seismicity associated with the 16 October 1999 Hector Mine earthquake. Data include epicenters from 10/99-2/01.

1999 rupture in color; other faults shown in gray.

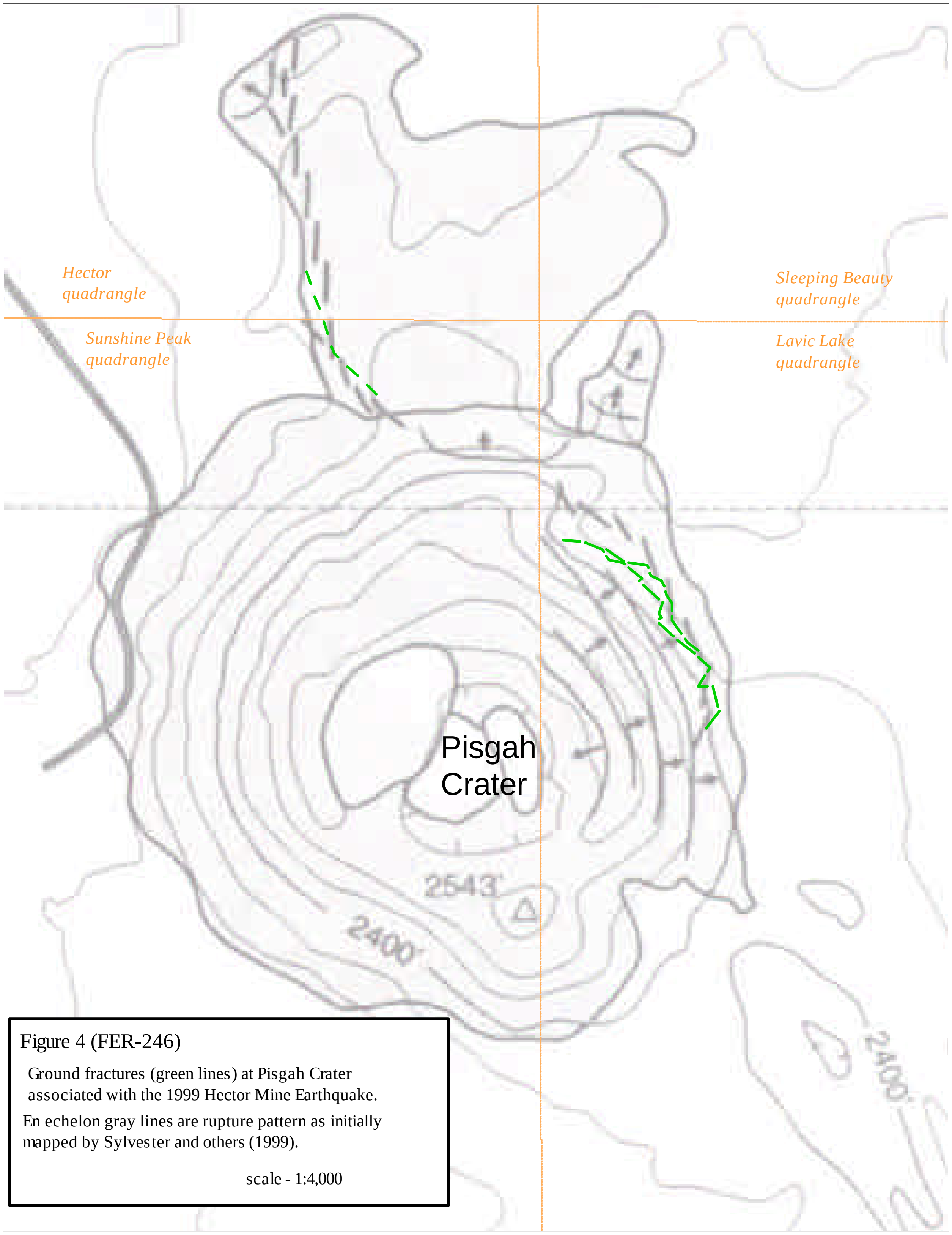

Figure 4 (FER-246)

Ground fractures (green lines) at Pisgah Crater associated with the 1999 Hector Mine Earthquake.

En echelon gray lines are rupture pattern as initially mapped by Sylvester and others (1999).

scale - 1:4,000

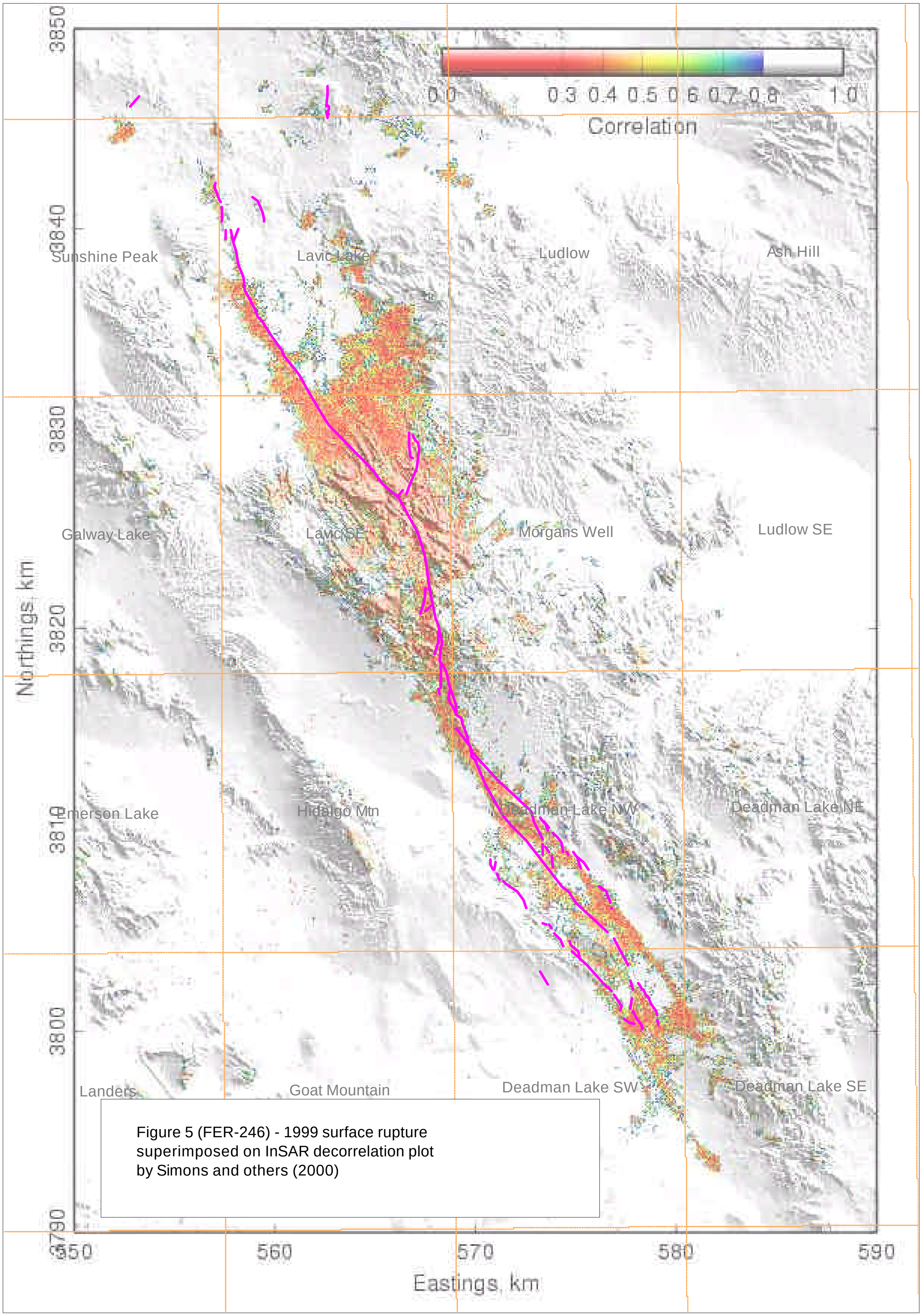

Figure 5 (FER-246) - 1999 surface rupture superimposed on InSAR decorrelation plot by Simons and others (2000)